Getting started

No-regrets strategies for reducing greenhouse gas emissions

Evan Mills, Deborah Wilson and Thomas B. Johansson

An integrated approach for choosing among energy supply- and demand-side measures shows that, compared to business-as-usual demand patterns, global greenhouse-gas emissions can be reduced well below current levels with net economic benefits *to society. Given these findings, a 'wait-and-see' stance towards new initiatives in energy and environmental policy is not economically justifiable. Achieving significant emissions reductions, however, will require commitments to policies aimed at enabling energy markets to function more efficiently and supporting legislation where market forces do not suffice.*

Keywords: Global warming; Greenhouse gases; Economics

Any strategy to reduce greenhouse gas emissions must involve the global energy system, because fossil-fuel-based energy consumption currently causes around 50% of global greenhouse forcing.[1] To stabilize atmospheric concentrations of the major greenhouse gases at today's levels will require immediate reductions of over 60% of current anthropogenic carbon dioxide (CO_2), nitrous oxide (N_2O) and chlorofluorocarbon (CFC) emissions and 15% to 20% reductions for methane (CH_4).[2] Can such reductions be accomplished, and would they be compatible with developing countries' ambitions and continued economic growth in the industrialized countries? If so, what would they cost?

These questions became especially relevant when the World Energy Conference (WEC) published projections in 1989 suggesting that global primary energy demand would grow by 76% by the year 2000 as economic growth proceeded, and that the associated CO_2 emissions would grow by 69% despite a three-and-a-half-fold increase in nuclear power capacity.[3]

Recent econometric studies suggest that significantly reducing CO_2 emissions will be very expensive.[4] This conclusion tempts policymakers to postpone any response to the climate change problem, and to wait instead for undisputed scientific proof that climate change is occurring. However, while the marginal costs of major reductions may be high, measures with no net cost compared to the 'business-as-usual' alternative are available for *beginning* to reduce emissions.

An energy strategy aimed at reducing greenhouse gas emissions at the least cost can combine different approaches: fuel switching, improved energy conversion efficiencies and improved energy end-use efficiencies. Many applicable technologies, especially end-use technologies, are presently available, but average efficiency levels do not come close to those of the best products on the market. Ongoing research and development work suggests that many more opportunities to reduce greenhouse gas emissions will become available. In this article, we describe a variety of existing and emerging energy supply and end-use technologies, their costs and their associated emissions savings, and case studies of their possible application in the USA, Sweden and the State of Karnataka, India. Finally, we present examples of policies to consider for realizing such opportunities.

Specific opportunities

Before making macro-level analyses covering entire sectors and geographical areas, it is necessary to review and compile data on specific measures for reducing greenhouse gas emissions. The net emissions associated with those measures, compared to a chosen base case, must then be estimated. These estimates can be combined with the incremental costs of choosing each measure *v* those for the

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base-case measures, in order to find the *net* cost (or benefit) of reducing emissions.

This section highlights some examples of the cost-effectiveness of measures to reduce greenhouse gas emissions, using economic evaluations reflecting a societal perspective. We compare fuels and technologies based on their costs without taxes and we use a societal discount rate of 6% (real) for calculating annual costs of supply and end-use efficiency investments. Our method of making these calculations is developed in Appendix 1 and a collection of examples is provided in Appendix 2.

To provide a more complete assessment of greenhouse gas emissions, we have considered more than just combustion-related CO_2. As a first step, we have included fuel-cycle emissions associated with the mining, processing, transporting and burning of fossil fuels. In some cases more than half of the emissions occur *before* the point of fuel combustion. We have also included greenhouse gases other than CO_2. Including a broader range of emissions (expressed in carbon equivalents) can lead to different rankings of measures. We found, for example, that if only CO_2 is counted, compressed natural gas (CNG) automobiles appear 'better' than gasoline-fueled cars. However, total greenhouse gas emissions are in fact greater for CNG automobiles after including the CO_2 releases from fuel production and related methane and N_2O emissions. The same reversal of rankings occurs for vehicles burning coal- and natural-gas-based methanol.

We find that all of the currently available end-use efficiency measures described in Appendix 2 (applicable to lighting, passenger cars, appliances, space heating, motors, etc) reduce emissions while providing a net economic *benefit* (ie savings) in the $100 to $500/tonne range.[5] Switching to biomass-based fuels for heating can also reduce emissions and provide a net economic benefit. Examples of biomass fuels include forest residues, agricultural wastes, by-products from the paper and pulp and sugar industries, and materials grown on plantations specifically for energy purposes. Burning renewably-grown biomass feedstocks results in zero net carbon emissions when the carbon emitted from burning the fuel is just equal to the carbon reabsorbed from the atmosphere as replacement biomass is grown.

For a given fuel, advanced commercially available electric power plants can also achieve emissions reductions at no net cost. Switching from coal to high-efficiency natural-gas-fired power plants avoids emissions and produces a net benefit of around $100/tonne of carbon equivalent. Switching to renewables at today's prices tends to result in net costs, but is expected to provide net benefits of around $100/tonne within 10 to 20 years.[6] Avoiding emissions by building new nuclear power plants would cost about $40/tonne of avoided carbon-equivalent emissions under today's US conditions *v* a benefit of $11/tonne for the industry's target costs.[7]

Efficiency opportunities

There are many cases in which a variety of technologies exist that serve the same function (ie, provide the same *service*) but require very different amounts of energy to do so. Efficient light bulbs, refrigerators, cars, motors, pumps, fans, and compressors are just a few examples. There is a large global potential for reducing energy requirements by introducing the most efficient technologies as replacements for the current equipment stock in the natural turnover cycle and as the stock grows. Many studies, four of which are described in this article, have been carried out that estimate the energy efficiency gains and emissions reductions achievable by applying efficient technologies. Physical and technical limits for these technologies are still far from being realized in most cases, thus continued research and development can continue to provide large returns.

Lighting. Lighting typically comprises 10 to 20% of electricity demand in developing and industrialized countries. Today, indoor lighting is often provided by incandescent lamps. As an example of providing lighting services with reduced energy input, a 15-watt compact fluorescent lamp can be used to replace a 75-watt incandescent lamp. The compact fluorescent lamp provides the same energy service (lumen output), but requires five-times less electricity to do so.

Efforts to promote energy efficiency often focus on lighting. In Europe, 33 utility programmes that used financial incentives to promote the use of compact fluorescent lamps achieved an average cost of conserved energy of ¢2.1/kWh, including all direct and indirect costs for lamps, administration, advertising, postage, etc.[8]

Significant amounts of energy can also be saved in conventional fluorescent lighting systems. The Swedish utility Vattenfall recently completed a lighting retrofit demonstration at their headquarters. By modifying their existing fluorescent systems to use efficient lamps, ballasts, daylighting controls, occupancy sensors and other measures Vattenfall achieved a cost-effective 71% reduction in the electricity used for lighting. The quality of office lighting was also improved markedly.

Passenger cars. The global fleet of gasoline-fueled vehicles emits larger quantities of greenhouse gases than any other category of end-use devices. In the USA the production, distribution and combustion of transportation fuels account for approximately 27% of all fossil-fuel-related CO_2 emissions.[9] Efficiency improvements effectively avoided more than 500 million tonnes (mt) of carbon-equivalent emissions between 1974 and 1985 (inclusive).[10] Emissions from new gasoline-fueled cars can be cut by over three-fourths through higher efficiencies, and can be virtually eliminated with vehicles that utilize non-fossil fuel sources.

Significant efficiency improvements have already been achieved in passenger cars: the average nominal (laboratory test) fuel efficiency for new passenger cars sold in the USA improved by 50% (to 8.4 litres/100km) between 1973 and 1986.[11] Of these efficiency gains 90% can be attributed to fuel-efficiency improvements as opposed to a shift in vehicle mix.[12]

A wide range of technologies are available today for further increases in the fuel-efficiency of new automobiles,[13] some of which can bring about improvements with negative to small positive costs. From an efficiency standpoint, one of the most advanced passenger-car prototypes is the Toyota AXV. This four- to five-passenger car has a fuel efficiency of only 2.4 1/100km.[14] A similar example is the Light Component Project prototype (LCP-2000) produced by Volvo. This four-passenger automobile passes the world's most stringent crash and emissions tests (ie, California's), achieves a fuel efficiency of 3.6 litres/100 km, and was designed to cost about the same to manufacture as an average subcompact car at a production level of 20 000 cars/year.[15] The Elsbett engine used in this car can be operated with biomass-derived fuels as well as gasoline.[16]

Many of the technological advances that can reduce fuel consumption in gasoline-fueled cars will be applicable to methanol cars as well. Because of the better combustion properties of methanol, methanol vehicles have an intrinsic potential for achieving fuel efficiencies that are up to 25% better than those for gasoline and compressed natural gas (CNG) vehicles.[17]

Efficient electric vehicle technology is in a rapid stage of development. General Motors, for example, has announced its intention to market its protoytype electric car: the Impact. This two-passenger car is expected to consume a mere 0.07 kWh/km (a gasoline equivalent of 1.7 1/100 km): only 14% of the primary energy consumption of the 1987 US stock-average gasoline-fueled vehicle.[18] As in the case of methanol, the amount of emissions from electric vehicles depends on the feedstock used, in this case to produce the electricity.

Supply opportunities

Modernization of power generation. The average conversion efficiency from primary fuels to electricity in new power plants has slowly improved in recent years. Vigorous R&D efforts underway during the 1980s resulted in maximum efficiencies of about 45% (on a higher heating value basis) for commercially available combined-cycle power plants fueled with natural gas.

The choice of fuel and conversion technologies has an important effect on the amount of greenhouse gas emissions from electric power production (Figure 1). Replacing average conventional coal-fired steam plants with pressurized fluidized-bed combustion plants (PFBC, also coal-based), reduces emissions by almost 20%. A *further* 48% reduction can be achieved by switching to natural gas and the best available combined-cycle power plants.

Power plant conversion efficiencies could be increased beyond currently-available levels with continued development of aeroderivative gas turbines. Through a combination of measures, such turbine designs currently reach 54% in natural-gas-fired systems.[19] The capital costs of these power plants ($500/kW) are estimated to be lower than those of new central-station, coal-steam plants with flue-gas desulphurization, nuclear or hydroelectric power plants.

The simultaneous production of electricity and useful heat (cogeneration) offers still higher emissions-reduction possibilities. The total system efficiencies of some cogeneration applications are well above 80%. Total system emissions can be minimized by combining the best available technologies to meet a given demand for electricity and heat. Figure 1 compares cogeneration systems with central-station plants that provide no useful heat. Cogeneration based on natural gas offers an additional 38% emissions reduction beyond the best available combined-cycle plants fired with natural gas. The plants with the lowest emissions also have the lowest costs.

The emergence of highly efficient gas turbines has provided new opportunities for utilizing gasified solid fuels such as biomass and coal. Advanced gas turbines using gasified coal have been demonstrated in coal-integrated-gasifier/gas turbines (CIG/GT). Advanced gas turbines fired with gasified wood (BIG/GT) have not been demonstrated, but detailed

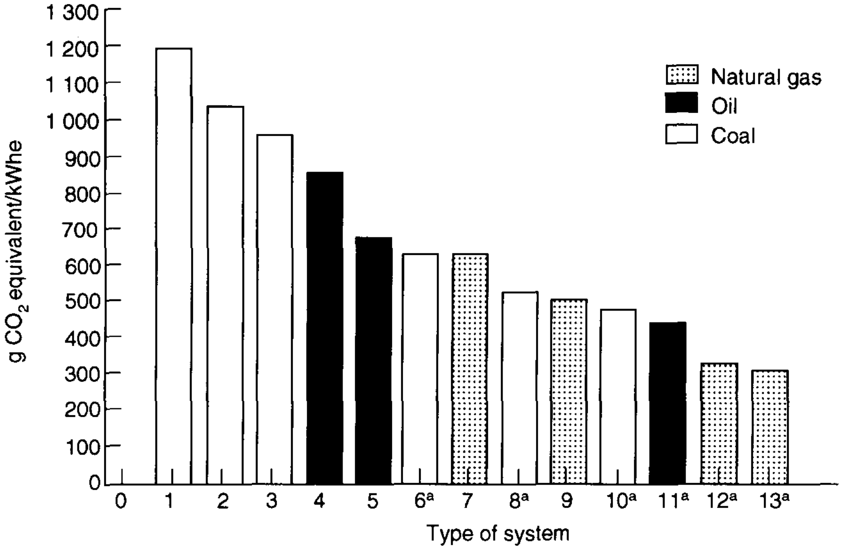

Figure 1. Greenhouse gas emissions from commercially-available power plants.

Notes: [a] = cogeneration. Greenhouse-gas emissions vary substantially among commercially-available technologies for producing heat and power. Central-station power plants are compared with cogeneration plants providing both useful heat and power. The energy requirement for electricity production using cogeneration technologies is taken as the total energy supplied minus that which would have been required to produce the heat independently (assuming a boiler efficiency corresponding to a lower-heating-value of 90%). All power plant efficiencies (Eff) are based on higher heating values. For the cogeneration systems, the power–to–heat ratios are given as E/H. The greenhouse gases are expressed as an equivalent amount of carbon dioxide (CO_2eq/kWhe). Methane and methane-related fuel-cycle emissions from coal, oil, and natural gas consumption are taken into account (see Appendix 1). 1. Average conventional steam turbine (coal, Eff 34%); 2. Best available steam turbine (coal, Eff 39%); 3. Pressurized fluidized bed combustion (PFBC) (coal, Eff 42%); 4. Average conventional steam turbine (oil, Eff 38%); 5. Best available combined-cycle gas turbine (oil, Eff 48%); 6. Cogeneration: average conventional steam turbine (coal, Eff 78%, E/H = 0.50); 7. Average combined-cycle gas turbine (natural gas, Eff 36%); 8. Cogeneration: best available steam turbine (coal, Eff 83%, E/H = 0.60); 9. Best available combined-cycle gas turbine (natural gas, Eff 45%); 10. Cogeneration: pressurized fluidized bed combustion (coal, Eff 86%, E/H = 0.65); 11. Cogeneration: best available steam turbine (oil, Eff 81%, E/H = 0.60); 12. Cogeneration: steam-injected gas turbine (natural gas, Eff 75%, E/H = 0.80) 13. Cogeneration: best available combined-cycle gas turbine (natural gas, Eff 77%, E/H = 1.0)

design studies indicate that it may be possible to commercialize them more quickly than CIG/GT schemes. This is because biomass is inherently cleaner and easier to gasify than coal and because the scale of demonstration plants is also appropriate for commercial applications.[20]

Modernization of sugar cane and alcohol industries. The sugar cane industries in developing countries offer a particularly promising area for the application of BIG/GT technologies. Sugar cane production yields two kinds of biomass fuel suitable for gasification: bagasse and barbojo. Bagasse is the residue from crushing the cane, and is thus available during the milling season; barbojo is the tops and leaves of the cane plant that could be harvested and stored for use after the milling season. Ogden *et al* calculate that by the year 2027 the 80 sugar cane producing developing countries could thus generate 70% more than their *total* 1987 electricity production from all sources. Moreover, the costs would be competitive with conventional sources of electricity based on fossil fuels.

The ethanol simultaneously produced from cane would be equivalent to about 9% of total oil-use in all developing countries in 1987. Odgen *et al* point out that were the electricity produced instead from coal, and were the alcohol and methane used instead of gasoline in the transport sector, the additional CO_2 emissions would equal nearly half of the total 1986 emissions from fossil fuels in developing countries.[21]

Solar electricity. Currently, about 1 500 MW of wind capacity and 300 MW of solar thermal capacity is installed in the USA, mostly in California. The electricity costs from these systems are in the ¢5 to ¢10/kWh range, and ongoing development work is expected to lower costs to the point where they will be cost-competitive for wholesale power generation.[22] Perhaps the most promising solar technology is the solid-state photovoltaic (PV) cell, which converts sunlight directly to electricity. The costs are presently ¢30 to ¢35/kWh, and projected by five US National Laboratories to drop to ¢4 to ¢5/kWh by 2020 to 2030.[23] About 40 MW of photovoltaic capacity is currently installed worldwide, with the greatest market in remote applications where the high costs are acceptable. Projections based on development work in the PV industry suggest that photovoltaics will become competitive with fossil-fuel power plants within a decade:

> The development of large-scale, computer-integrated manufacturing lines should decrease the manufacturing costs of amorphous silicon solar cells to less than $1/W$_p$ by the early 1990s, leading to the development of both residential and central station utility applications in the mid-to-late 1990s.[24]

Global, national and regional examples

What are the likely future economic and emissions impacts of individual measures such as those we have described, if combined and applied at the global, national or regional levels? Evaluations aimed at answering this question must begin by assuming a certain level of economic growth. The economic growth rates (and embedded assumptions regarding growth in material output and demographic factors) can then be used to project the future demand for energy services. Once a demand level for energy services is determined, specific technologies for providing them can be evaluated and compared. Before proceeding to scenarios, we make a few points about projecting the future demand for energy services.

Energy, development and economic growth

History has shown that the link between economic growth and growth in energy demand has been broken, and there are good reasons to believe that there need not be a recoupling. In contrast to the trends for total energy consumption, electricity-use has tended to grow faster than GDP. However, growth in electricity/GDP in many countries including the USA, the UK, Japan, and West Germany slowed to zero in the mid-1970s and declined thereafter.[25]

The perhaps counter-intuitive decoupling of energy demand and GDP growth occurs as a result of three on-going types of change: (1) structural changes in consumption patterns, towards fewer energy- and materials-intensive products and activities, that take place as development in a country proceeds; (2) shifts towards products that are less energy- and materials-intensive; and, (3) improvements in energy conversion and end-use efficiencies.[26] The combined effect of these changes has been to reduce national energy intensity, even where there are no formal policies to promote the changes.

Significant errors can be introduced into energy demand projections if these fundamental trends are ignored. For example, even if developing countries choose to follow the conventionally projected development path, structural and technological trends will enable them to be much less energy-intensive than their northern neighbours. With an effective set of national and international policies, the trend toward reduced energy intensity can be accelerated in both industrialized and developing countries.

A global view

Goldemberg *et al* found that by using efficient end-use technologies all of the energy services associated with a significant increase in the standard of living in both developing and industrialized countries can be attained by the year 2020 with only a 10% increase in global primary energy-use.[27] This is much lower than the increases in global energy-use projected by the WEC and others. The scenario results in a 10% decline in fossil-fuel CO_2 emissions compared to 1980, using a conventional mix of energy sources, but relatively less reliance on coal. To achieve greater reductions, end-use efficiency measures need to be combined with increased use of non-fossil energy sources.

Industrialized countries

An example from the USA. The USA reduced its energy intensity by approximately 25% between 1973 and 1986. Today's supply and end-use technologies offer the prospect for significant additional efficiency gains.[28]

Possibilities for avoiding carbon emissions in the near term are shown as a function of cost for the USA in Figure 2. Each step in the figure corresponds to an end-use efficiency measure or a supply strategy that saves energy and reduces emissions at a given net benefit or cost compared to the current US Department of Energy (DOE) forecast for the year

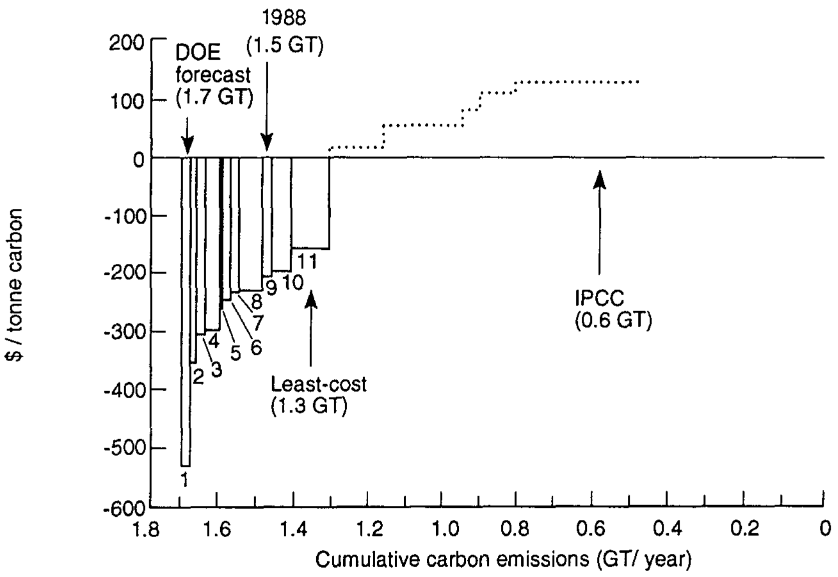

Figure 2. Net cost of avoiding emissions: USA in 2000.

Notes: The x-axis shows total national carbon emissions reductions achievable through the adoption of the 11 cost-ranked measures listed below.[52] The upper limit (1.7 GT) represents the current US DOE forecast for the year 2000. The IPCC label indicates the level of reductions necessary to stabilize atmospheric concentrations of greenhouse gases, according to the Intergovernmental Panel on Climate Change. The y-axis indicates the net cost of implementing each measure. Negative costs reflect a net economic benefit compared to the DOE forecast. The average net economic benefit for steps 1–11 is $231/tonne. 1. Raise the Federal gasoline tax by ¢12/litre within five years and spend part of the revenue on mass transit and energy-efficiency programmes; 2. Use white surfaces and plant urban trees to reduce air conditioning loads associated with the summer 'heat island' effect in cities; 3. Increase the efficiency of electricity supply through development, demonstration, and promotion of advanced generating technologies; 4. Raise car and light truck fuel-efficiency standards, expand the gas-guzzler tax, and establish gas-sipper rebates: new cars average 5.2/100km and new light trucks average 6.71/100km by 2000; 5. Reduce Federal energy-use through life-cycle cost-based purchasing; 6. Strengthen existing Federal appliance efficiency standards; 7. Promote the adoption of building standards and retrofit programmes to reduce energy-use in residential and commercial buildings; 8. Reduce industrial energy-use through R&D programmes, promotion of cogeneration, and further data collection; 9. Adopt new Federal efficiency standards on lamps and plumbing fixtures; 10. Adopt acid rain legislation that encourages energy efficiency as a means for lowering emissions and reducing emissions control costs; 11. Reform Federal utility regulation to foster investment in end-use efficiency and cogeneration.

2000. The forecast assumes 2.5% real economic growth.

In the DOE forecast, US carbon emissions would increase by 200 million tonnes/year by the year 2000 (13% of 1988 emissions). In contrast, 11 policy strategies for the year 2000 would lead to an emissions reduction of 170 mt (11%) from 1988 levels – similar to the global opportunity just described – and a cost *reduction* of $85 billion/year compared to the DOE forecast. The emissions reductions are accompanied by an average economic benefit (savings) of $231/tonne.[29]

These results reflect only 11 specific policies that pertain mostly to improved end-use efficiency, and are achievable over a period of 10 years. Renewable supply-side strategies are not included. Thus, the avoided carbon emissions represent only part of the long-run potential. For example, the use of biomass in electric power and heat production has not been included. This option is illustrated in the following example of an integrated supply–demand approach.

An integrated example from Sweden. The situation in Sweden presents an interesting case of balancing climate change issues with other energy policy goals. Sweden uses more nuclear-generated electricity per capita than any other country. In 1980 a public referendum called for a full phase-out of nuclear power. The referendum led to a parliamentary decision to phase out the country's 12 nuclear power plants by 2010. Sweden has also committed to holding CO_2 emissions at or below 1988 levels and

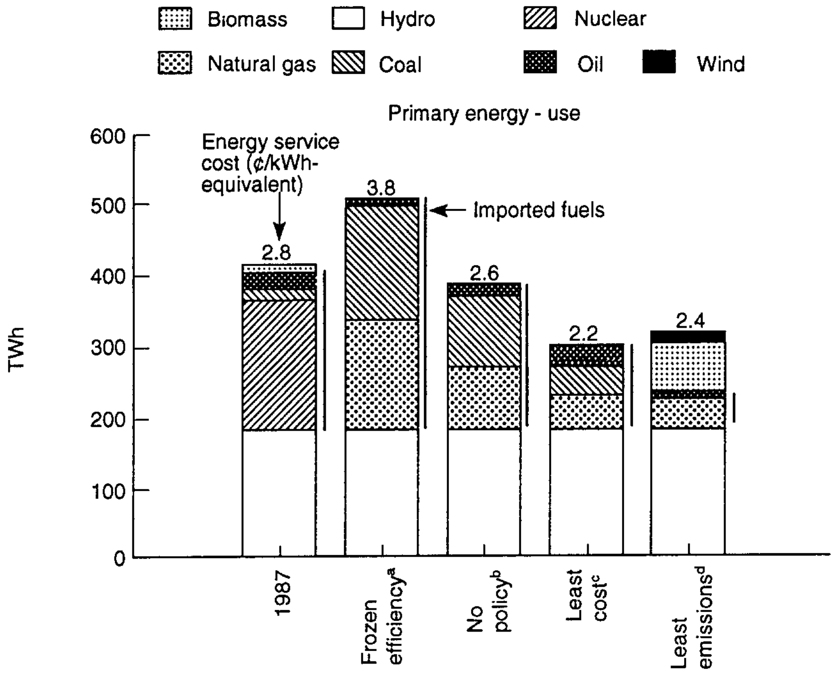

Figure 3. Swedish primary energy, energy service costs (efficiency investments and purchased energy) and energy import dependence: 1987 and scenarios for 2010.

Notes: All services derived from electricity, district heat, and 15 TWh of industrial process heat are incorporated. Electricity from hydroelectric, nuclear, and wind power is converted to its fuel equivalent using a 36% thermal efficiency. Electricity demand in the least-cost and least-emissions scenarios is 25% lower than 1987 levels. In contrast, electricity-use increases by 9% in the no-policy scenario. All scenarios include a complete phase-out of nuclear power by 2010, as called for by the Swedish government. [a] Frozen-efficiency baseline. End-use efficiencies do not improve beyond 1987 (base-year) levels. Electricity demand is met with existing non-nuclear power plants and by new efficient power plants half fueled by coal and half by natural gas. CHP is used extensively, both for industry and municipal district heating. [b] No-policy scenario. In this scenario, no new policies are implemented to increase the efficiency of electricity-use or to increase the use of renewable supply sources. The scenario includes only those efficiency improvements that are expected to result from a cost-driven average 50% increase in real electricity prices. The energy supply mix for electricity production is the same as in the frozen-efficiency baseline. [c]Least-cost scenario. This scenario goes beyond the no-policy scenario to show the impact on electricity demand if the most efficient technologies (for appliances, motors, lighting, etc) available today or near commercialization were introduced at the natural rate of capital turnover up to the year 2010. Also included is some fuel switching in heating systems that can currently use electricity in combination with other fuels. Only those measures costing less than the electricity they save are employed. The energy supply mix from the preceding scenario is retained. [d] Least-emissions scenario. This scenario begins with the end-use measures included in the least-cost scenario and introduces gasified biomass fuel for electricity production (replacing fossil fuels). A small amount of wind-generated electricity is also included. Natural gas is used after available biomass resources are allocated.

abstaining from constructing hydroelectric plants on the country's four remaining wild rivers. Hence, Sweden offers an acid test of energy planning in the face of potentially conflicting national policy goals.

Possibilities for meeting these goals were identified in a detailed assessment recently completed by Vattenfall (the Swedish State Power Board) and the University of Lund.[30] The boundary conditions encompass the energy services provided in the base-year (1987) by electricity, cogeneration, district heat, and some industrial process heat: 63% of total primary energy supply in Sweden.[31] Four electricity demand scenarios were developed, each incorporating the structural and demographic expansion associated with an anticipated 54% increase in real GNP to the year 2010, as assumed by the Ministry of Finance.

Figure 3 shows the types of fuels used to supply

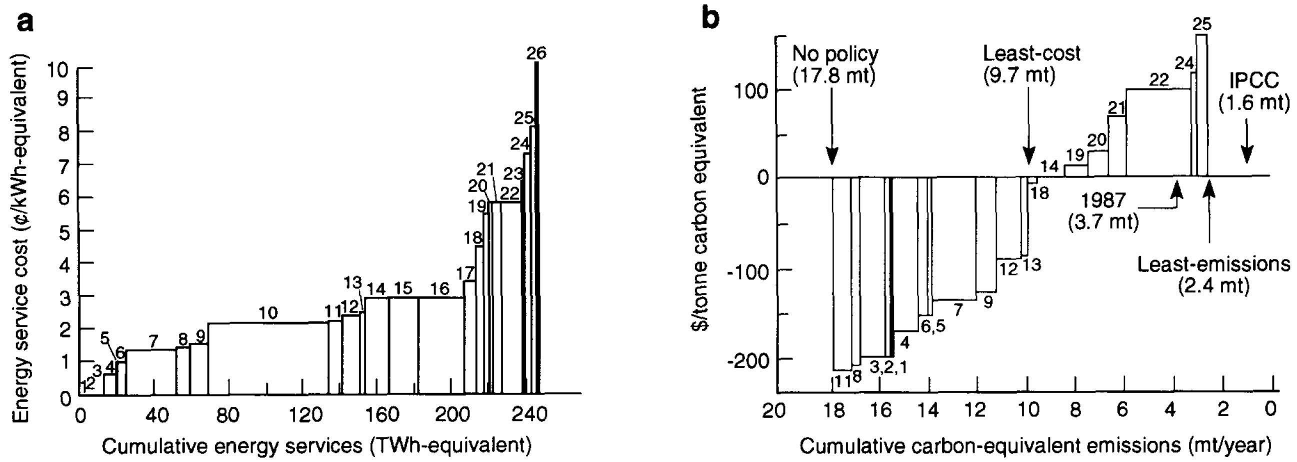

Figure 4. An integrated resource supply curve for Sweden in 2010 (Figure 4a) and the corresponding net costs of avoiding greenhouse gas emissions (Figure 4b).

Notes: Each step represents a particular supply or demand-side measure (see key) used to meet the total demand for energy *services*, ie the frozen-efficiency scenario (denoted in TWh-equivalents) projected for the year 2010. Figure 4a reflects the least-emissions scenario described in Figure 3. The width of each step in Figure 4a shows the energy provided or conserved by the measure. The height of each step is the measure's levelized cost/kWh-equivalent (using a 6% real discount rate). The net costs of avoiding emissions shown in Figure 4b reflect technology changes in the power and heat sector between 1987 and 2010 (eg existing hydroelectric plants are not shown). The horizontal axis shows greenhouse gas emissions (as carbon-equivalents) for the various scenario levels given in Figure 3. The vertical axis indicates the net cost of achieving the emissions reductions for each measure (using the method described in Appendix 1). Negative costs reflect a net economic benefit compared to the no-policy scenario.[53] Rankings shift in some cases between Figures 4a and 4b because the type and amount of avoided emissions varies depending on the measure. The IPCC label indicates the level of reductions necessary to stabilize atmospheric concentrations of greenhouse gases, according to the Intergovenmental Panel on Climate Change. *Key:* 1. Residential space heating (including effect of existing standards); 2. Conversion of large heat pumps; 3. Efficient electronic office equipment; 4. Efficient appliances (excluding lighting); 5. Efficient lighting – residential, incandescents; 6. Efficient lighting – commercial and industrial, incandescents; 7. Efficient motors, pumps, fans, compressors, etc; 8. Fuel switching to gas from electricity; 9. Efficient lighting – commercial and industrial fluorescents; 10. Existing hydroelectric plants; 11. Fuel switching to oil from electricity; 12. Miscellaneous efficiency improvements; 13. Efficient commercial food preparation; 14. Supplemental district heating (biomass); 15. Industrial process heat from cogeneration; 16. District heating from cogeneration; 17. Existing industrial cogeneration – electricity; 18. Heat pump – existing electric boiler; 19. Industrial cogeneration with biomass; 20. Cogeneration, biomass – (*v* existing cogeneration); 21. Cogeneration, biomass – (*v* new central station); 22. Cogeneration, biomass – (*v* new cogeneration); 23. Existing oil condensing plants; 24. Heat pump – existing direct electric; 25. Wind turbines; 26. Existing gas turbines.

the electricity and heat required in the four scenarios, the portion of this energy that is imported, and the resulting costs per unit of energy services provided (for purchased energy plus efficiency investments). Energy import dependence drops from today's value of 54% to 38% in the least-cost scenario and to 11% in the least-emissions scenario.

The means of providing energy services in the least-emissions scenario for 2010 are depicted in Figure 4a. This 'integrated resource supply curve' includes 26 steps representing demand-side efficiency improvements and supply options, including existing supply systems such as hydroelectric power, that are projected to be used in 2010. The steps are ranked by increasing cost of delivered energy services (¢/kWh-equivalent). The integrated resource supply curve improves upon the familiar conservation supply curve by explicitly incorporating the size and costs of various supply options, rather than assuming a generalized cut-off point beyond which energy-efficiency is not cost-effective. This is important given that supply-side options vary in cost and in their potential contribution to the energy system.

The cumulative greenhouse gas emissions avoided by each change from the existing system (20 steps) are shown in Figure 4b, where the measures are re-ranked in order of increasing cost of avoided emissions. The no-policy scenario results in annual emissions of 17.8 mt carbon-equivalent in the year 2010, a sixfold increase from 1987 levels. These emissions are reduced by 44% in the least-cost scenario but are 165% higher than base-year emissions. This situation is amended in the least-emissions scenario by bringing biomass (and a small amount of wind-generated electricity) into the supply mix. In this scenario, emissions decline to only 2.4 mt: 35% below actual 1987 levels.

The projected (no-policy scenario) emissions are avoided at an average net economic benefit to society of $41/tonne. This net benefit, however, is $102/tonne carbon-equivalent less than the benefit derived from the least-cost case. The $102/tonne difference between the two cases can be viewed as the net economic cost (value) to Sweden of achiev-

Table 1. Alternative commercial energy-use scenarios for developing countries.[50]

	1985	2025[a] Goldemberg *et al*		RCWP[b]	RCW[b]
Final energy (EJ)					
Fuel	55.0	149.4	(2.5)	150.0 (2.5)	170.1 (2.9)
Electricity	5.6	26.5	(4.0)	35.1 (4.7)	39.9 (5.0)
Total	60.6	175.9	(2.7)	185.1 (2.8)	210.0 (3.2)
Primary energy (EJ)					
Fossil fuel	71.0	124.5	(1.4)	132.6 (1.6)	242.8 (3.1)
Hydro	6.5	20.5	(3.7)	33.2 (4.3)	28.9 (3.9)
Nuclear	0.7	1.4	(1.9)	13.8 (7.7)	14.3 (7.8)
Biomass	0.0	76.5		76.5	4.8
Solar	0.0	6.7		17.0	5.2
Total	78.2	229.6	(2.7)	273.1 (3.2)	296.0 (3.4)
Carbon emissions (GT)	1.5	2.2	(1.0)	2.9 (1.7)	5.4 (3.3)

[a] Average growth rates (in %/year) for the period 1985–2025 are given in parentheses.
[b] These are the projections made by the US Environmental Protection Agency (EPA) for its rapidly changing world (RCW) scenario and its rapidly changing world with policy (RCWP) scenario.[51]

ing reductions beyond the point where the individual measures can be implemented with no net cost to society.[32] The carbon taxes introduced in Sweden in 1991 are \$150/tonne, suggesting that the \$102/tonne premium is well within the bounds seen as reasonable by the Swedish government.

Developing countries

Future greenhouse gas emissions in developing countries are of special concern because of the rapidly growing demand for energy services there. Energy, however, need not constrain development of the material standard of living in these countries.[33] Encouraging technological 'leapfrogging' to reduce the cost of energy services (ie, the adoption of technologies that are more efficient than the average in industrialized countries) must become a major objective in development policy.

Two scenarios for developing countries (for supply and demand respectively) indicate that fossil-fuel carbon emissions can be constrained to 2.2 GT/year in 2025.[34] In the supply scenario, natural gas and oil each contribute one-third of the commercial fuel supply, and most of the balance is met with biomass (Table 1). In comparison, the US Environmental Protection Agency (EPA) has estimated that emissions in developing countries will grow to 5.4 GT/year by 2025.[35] The EPA estimate does not include new policy initiatives aimed at reducing emissions.

An integrated example from Karnataka, India. The official long range plan for power projects (LRPPP) for the electricity sector in Karnataka projects a more than threefold expansion of electricity generation and consumption between 1986 and 2000. In meeting this projection, the plan calls for annual expenditures of \$3.3 billion/year and expansion of coal-fired electricity generation capacity, resulting in a 0.83 million tonne (127%) increase in annual carbon emissions from current levels.

An alternative scenario developed for Karnataka by the Department of Management Studies at the Indian Institute of Science would provide a much higher level of electricity services than the LRPPP plan.[36] Electricity demand in this scenario, however, only doubles between 1986 and 2000, as a result of investments in efficiency-improvement measures and the introduction of solar water heating and LPG stoves. The additional demand is met with cogeneration in sugar factories, mini/micro hydroelectric systems, and decentralized rural power generation based initially on biomass and later on photovoltaics. Annual expenditures of \$0.6 billion are called for, and annual carbon emissions increase by 0.004 million tonnes. The net economic benefit of this scenario compared to LRPPP plan is over \$3 000/tonne of avoided carbon emissions. The scenario illustrates that, even in developing countries, increasing electricity service levels and, thereby, living standards need not lead to emissions increases.

Policies

Although some of the technologies incorporated in the scenarios described above would be adopted under current market conditions, others would not. The opportunities lost when *inefficient* new vehicles, equipment and buildings are added to the stock are of primary importance.

Existing markets can not be relied upon to lead to the sufficient use of technologies that cost-effectively reduce greenhouse gas emissions because: (1) biases towards conventional supply systems lead to under-investment in energy efficiency; (2) consumers lack sufficient information, financing and access to the full spectrum of available equipment; and, (3) energy prices normally do not reflect marginal costs or the costs of externalities, such as climate change.

Despite the fact that the global end-use scenario described earlier is consistent with plausible values of income and price elasticities, and with energy prices not much higher than those at present,[37] market failures are steering the energy sector towards a future with much higher energy demand and greenhouse gas emissions. New policies are required to remedy this situation.

The kinds of policies described below are within the sphere of government-level policymaking. We indicate the general nature of such policies and offer a few examples of their application. Specific policies and their implementation must be chosen to fit the cultural, political and market conditions of each nation.[38]

- **Redefining the mission of energy suppliers and creating new markets for energy efficiency or emissions offsets can help build markets for energy services rather than energy *per se*.**[39] Some US utilities have more than a decade of experience with operating informational and financial-incentive programmes to promote energy efficiency.[40] As noted earlier, a number of European electric utilities have used financial incentives to promote energy-efficient lighting. In a new entrepreneurial initiative, the Swedish utility Vattenfall is spending $150 million (1 billion kroner) to help finance the kinds of end-use technologies described earlier in the least-emissions scenario. Some electric utilities in the USA have gone a step further by implemented innovative auction systems in which vendors of energy-efficiency services are able to compete with power plant suppliers.

  Creating markets for tradeable emissions offsets is another promising and economically efficient way to stimulate investments in energy efficiency. This is exemplified by recent amendments to the US Clean Air Act that set limits on total SO_2 emissions by individual utilities. Utilities emitting less than their SO_2 allowance – eg by increasing energy efficiency – can sell the excess emissions rights to other utilities.
- **Governments and other large buyers of energy-using equipment can use innovative procurement systems to promote the design and commercialization of more efficient products.** The Swedish National Energy Administration, for example, has cooperated with the largest building-management companies in Sweden to submit efficiency-oriented procurement proposals to appliance manufacturers. As a first step, this group has invited the manufacturers to produce new refrigerator-freezer designs that feature improved energy efficiency. The result has been positive: new units will be commercialized in 1991 that achieve 55% lower electricity-use than the most efficient models now on the market, while eliminating CFCs from the insulation.[41]
- **Emissions taxes can be used to signal the need to lower emissions, to fund implementation of measures that achieve emission reductions and to create funds for research, development and demonstration (RD&D).** To generate US$30 billion/year would only require a $1/bbl-equivalent charge on fossil fuels.[42] Such a tax would be important, but, for institutional and other reasons, the charge would not in itself create a significant impact on the market.[43]
- **Energy performance standards should be introduced when market failures inhibit the attainment of optimal end-use efficiency goals.** Automobile efficiency opportunities offer an instructive example. The total cost of owning and operating an automobile is essentially constant over a wide range of fuel economies,[44] resulting in the lack of an incentive for improved energy efficiency. As a remedy for this type of problem, standards have been used in many countries. For example, the USA has fuel-efficiency standards for automobiles, buildings and household appliances, and standards are pending at the State or national level for motors, lighting and other technologies.[45] Energy-performance standards are a logical extension of safety and other standards now in place to protect both consumers and the environment. Society benefits from energy-performance standards that maintain energy service levels while yielding a reasonable return on the investments associated with increased energy efficiency.
- **RD&D priorities can be changed to reflect the most promising strategies for combating climate change.** The current funding priorities of International Energy Agency member governments are indicated in Figure 5. Nuclear ener-

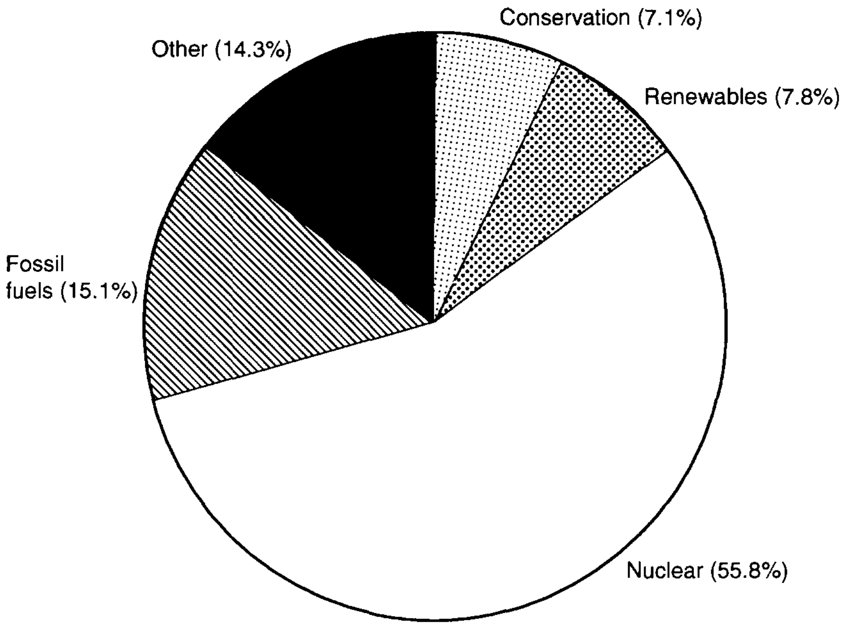

Figure 5. RD&D budgets (US$6.88 billion) in International Energy Agency governments, 1988.[54]

gy is receiving over half of the funding, despite its limited potential to reduce greenhouse gas emissions or the cost of energy services,[46] and despite the fundamental security problem of creating weapons-proliferation-proof nuclear energy systems.[47] As of 1988, end-use efficiency received only 7% of the countries' RD&D budgets and renewable energy sources received 8%. The share of total RD&D allocated to energy efficiency and renewable energy declined between 1977 and 1988.[48] In a strategy to abate global climate change, renewable sources and energy efficiency should become the major focus for government-sponsored R&D because of their long-term potential to reduce emissions, their security-enhancing benefits, their present costs and the small size of the existing industrial base.[49]

Observations and conclusions

The examples we have shown for the USA and Sweden suggest that industrialized countries can significantly reduce their energy sector greenhouse gas emissions within 10 to 20 years by implementing measures with no net economic costs to society. Our example from a developing country (the state of Karnataka in India) suggests that emissions can be constrained to current levels at a net economic benefit, even with a doubling of electricity supply and even greater growth in the level of energy services delivered.

A commitment to implementing policies can be justified on its economic merits alone. A wait-and-see policy is economically inefficient, and also forgoes non-economic benefits to society, such as enhanced national/international security and the reduced environmental impacts beyond those associated with climate change.

Our results show much lower costs for reducing greenhouse gas emissions than those arrived at using econometric models. Our methods differ from econometric methods in several important respects. We focus on emissions reductions that can be achieved now while ensuring a reliable supply of the energy *services* required for desired development and economic growth. Taking an end-use perspective enables us to incorporate new factors that cannot be accounted for by models based on observations of the past. It also enables us to identify existing market failures and to analyse policy options aimed at making markets work better.

Despite our conclusion that something, indeed quite a bit, can be done, the strategies that we have described are not sufficient to achieve the approximately 60% emissions reductions required to stabilize atmospheric concentrations of greenhouse gases in the long term. Ongoing and accelerated technological development, reforestation and structural and behavioural changes not analysed in this article offer prospects of further emissions reductions. It is important to begin *now* with measures that are economically justified, rather than waiting until a detailed strategy for meeting long-run emissions-reductions targets can be developed.

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[1]Intergovernmental Panel on Climate Change (IPCC), *Policymakers Summary of the Formulation of Response Strategies*, report prepared for IPCC by Working Group III.
[2]IPCC *Policymakers Summary of the Scientific Assessment of Climate Change*, report prepared for IPCC by Working Group I, 1990.
[3]World Energy Conference, *World Energy Horizons: 2000–2020*, Editions Technip, Paris, 1989.
[4]A.S. Manne and R.G. Richels, 'CO_2 emission limits: an economic cost analysis for the USA', *The Energy Journal*, Vol 11, No 2, pp 51–74. For a critique of Manne and Richels article, see R.H. Williams, 'Low cost strategies for coping with CO_2 emission limits', *The Energy Journal* Vol 11, No 4, pp 35–59.
[5]Monetary values are in US dollars throughout this article.
[6]Solar Energy Institute, *The Potential of Renewable Energy: An Interlaboratory White Paper*, Solar Energy Research Institute Report, SERI/TP-260–3674, 1990.
[7]Based on a total busbar cost of ¢5.68/kWhe for current light-water technology (6% real discount rate, 30-year amortization): plant size (1 100 MW), capital costs ($3 060/kW), and efficiency (33.4%). The capital cost drops to $1 670/kW for the target light-water reactor. These estimates are from the Electric Power Research Institute (EPRI). The nuclear fuel-cycle cost $0.84/GJ (¢1.11/kWhe: EPRI's projection for 1990 to 2000) and the operations and maintenance costs (¢0.91/kWhe) are the 1985 US averages for nuclear plants. This busbar-cost derivation is shown in R.H. Williams and E.D. Larson, 'Expanding roles for gas turbines in power generation', in T.B. Johansson, B. Bodlund and R.H. Williams, eds, *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications*, Lund University Press, Sweden, 1989, p 525.
[8]The indirect costs of implementing measures vary according to many factors. Performance standards, for example, can have a negligible cost per unit of energy saved while costs can be higher for conservation programmes, especially during initial 'learning' periods. European lighting efficiency programmes have shown implementation costs of only ¢0.3/kWh, ie approximately 1/20 the cost of the energy they save. See E. Mills, 'Evaluation of European lighting programmes: utilities finance energy-efficiency, *Energy Policy*, Vol 19, No 3, April 1991, pp 266–278.
[9]M. DeLuchi, R.A. Johnston and D. Sperling, 'Transportation and the greenhouse effect', *Transport Research Received*, No 1175, pp 33–44.
[10]Calculated using data from US Department of Energy, *Annual Energy Review 1988*, Report DOE/EIA-0384(88), Energy Information Administration, 1989.
[11]S.C. Davis, D.B. Shonka, G.J. Anderson-Batiste and P.S. Hu, *Transportation Energy Data Book: Edition 10*, Oak Ridge National Laboratory, Report ORNL-6565, Oak Ridge, TN, USA, 1989. Unless stated otherwise, single-figure fuel economies are weighted averages of highway (45%) and city (55%) mileage, as per the USEPA test procedure. Note: miles per gallon (mpg) = (235)/(litres per 100 km).
[12]This analysis applies to the 1976 to 1988 period. See M. Ross 'Energy and transportation in the United States', *Annual Review of Energy*, No 14, pp 131–171.
[13]D.L. Bleviss, *The New Oil Crisis and Fuel Economy Technologies: Preparing The Light Transportation Industry for the 1990s*, Quorum Books, 1988, p 268.
[14]Toyota, press release, 23 October 1985.
[15]Bleviss, *op cit*, Ref 13.
[16]R.W. Mellde, I.M. Maasing and T.B. Johansson, 'Advanced automobile engines for fuel economy low emissions, and multifuel capability', *Annual review of Energy*, No 14, pp 425–444.
[17]See S. Unnasch, C.B. Moyer, D.D. Lowell and M.D. Jackson, *Comparing The Impacts of Different Transportation Fuels on the Greenhouse Effect*, California Energy Commission, Consultant Report P500–89-001, 1989. The environmental implications of moving toward methanol vehicles are highly dependent on the feedstock used for methanol production. The prime attractiveness of methanol vehicles lies in the opportunity to use biomass feedstocks. However, creating a methanol vehicle fleet would also create a market for methanol produced from coal feedstocks. This eventuality should be avoided because producing, transporting, and burning coal-based methanol leads to higher greenhouse gas emissions than gasoline, compared on a per-vehicle-kilometre basis; see C. Difiglio *et al*, 'Cost effectiveness of future fuel economy improvements', *The Energy Journal*, Vol 11, No 1, pp 65–86. It should be noted that methanol vehicles are potential emitters of large quantities of formaldehyde: a highly toxic gas that can also contribute to the production of tropospheric ozone. Formaldehyde emissions can be kept very low, however, through the use of methanol engines with oxidation catalysts, see D. Sperling and M.A. DeLuchi 'Transportation energy futures', *Annual Review of Energy*, No 14, pp 375–424.
[18]This is the fuel economy in urban driving conditions. Due to the regenerative breaking system in the Impact, urban and highway mileage are about equal. Personal communication, Mr Sloane, Public Relations, General Motors Detroit, 2 August 1990. The gasoline equivalent was computed using an electrical conversion efficiency of 45% and assuming 3.96 MJ/kWh which includes 10% transmission and distribution losses.
[19]California Energy Commission, *Chemically Recuperated Gas Turbine*, Report number P500–90–001 (draft), 1990.
[20]E.D. Larson, P. Svenningson and I. Bjerle, 'Biomass gasification for gas turbine power generation', in Johansson *et al*, *op cit*, Ref 7.
[21]This discussion is based on J.M. Ogden, R.H. Williams and M.E. Fulmer, *Cogeneration Applications of Biomass Gasifier/Gas Turbine Technologies in the Cane Sugar and Alcohol Industries*, Center for Energy and Environmental Studies, Princeton University, NJ, USA, 1990. The electricity production potential is 2 780 TWh_e/year. The potential contribution of barbojo depends on how much of the resource can be covered cost-effectively. By utilizing only bagasse fuel in this estimate, 900 TWh could be produced, or 55% of 1987 electricity demand. (Based on note c to Table 13 of Ogden *et al.*) This scenario uses biomass-integrated gasifier technology with intercooled steam-injected gas turbines (BIG/ISTIG). The scenario is calculated assuming growth in sugar cane production of 3%/year (the historical rate of annual growth since 1960) over the 40-year period. Half of the growth is assumed to be committed to sugar production (equivalent to the World Bank projection of the sugar demand growth rate to 1995) and half to the alcohol production. This much more efficient use of potential cane resources would considerably improve the economics of the cane industry, and in effect turn it into an electricity-production industry with sugar and/or alcohol as marketable byproducts.
[22]Solar Energy Research Institute, *op cit*, Ref 6.
[23]*Ibid.*
[24]D. Carlsson, 'Low-cost power from thin-film photovoltaics', in Johansson *et al*, *op cit*, Ref 7, p 595.
[25]Personal communication, Lars Nilsson, Department of Environmental and Energy Systems Studies, University of Lund, July 1990, based on R. Summers and A. Heston, 'A new set of international comparisons of real product and price levels estimates for 130 countries, 1950–1985', *Review of Income and Wealth*, No 1–25; and United Nations, *Energy Statistics Yearbook*, New York, USA, 1988.
[26]R.H. Williams and E.D. Larson, 'Materials, affluence, and industrial energy use', *Annual Review of Energy*, No 12, pp 99–144.
[27]J. Goldemberg, T.B. Johansson, A.K.M. Reddy and R.H.

Williams, *Energy for a Sustainable World*, Wiley-Eastern, New Delhi, 1988. Also summarized under the same title by the World Resources Institute, Washington, DC, 1987. The standard of living in developing countries is assumed to increase to that of the WE/JANZ regions, and by 50 to 100% in the industrialized countries.

[28]E. Mills, J.P. Harris and A.H. Rosenfeld, *Le Gisement d'Economies d'Energie aux Etats-Unis: Tendances, Perspectives et Propositions*, Energy Internationale, 1988–89, pp 169–193 (in French). Also as, 'Developing demand-side energy resources in the United States: trends and policies', Lawrence Berkeley Laboratory, Report No 24920, CA, USA.

[29]See *Notes* to Figure 2 for details.

[30]B. Bodlund, E. Mills, T. Karlsson and T.B. Johansson, 'The challenge of choices: technology options for the Swedish electricity sector', in Johansson *et al*, *op cit*, Ref 7.

[31]Using OECD conventions for counting nuclear and hydroelectric power.

[32]The marginal cost curve of avoided emissions is very steep. The marginal cost, in this case the cost of wind energy replacing fossil fuels, is \$135/tonne. This reflects today's wind energy costs (¢7/kWh). At projected future costs of ¢3.3/kWh (see Table 1), the marginal cost becomes a net benefit of \$41/tonne.

[33]J. Goldemberg, T.B. Johansson, A.K.N. Reddy and R.H. Williams, 'Basic needs and much more with one kilowatt per capita', *Ambio*, No 14, pp 190–200.

[34]J. Goldemberg, T.B. Johansson, A.K.N. Reddy and R.H. Williams, 'Energy for a sustainable world: an update, with emphasis on developing countries', presented at the *Bellagio Seminar on Energy Efficiency for a Sustainable World*; Goldemberg *et al*, *op cit*, Ref 33.

[35]US Environmental Protection Agency, *Policy Options for Stabilizing Global Climate*, D.A. Lashof and D.A. Tirpak, eds, Office of Policy, Planning, and Evaluation, Washington, DC, USA, (draft).

[36]A.K.N. Reddy, G.D. Sumithra, P. Balachandra and A. d'Sa, *Energy Conservation in India: A Development-Focused End-Use-Oriented Energy Scenario for Karnataka, Part 2 – Electricity*, Department of Management Studies, Indian Institute of Science, Bangalore, India, presented at the Bellagio Seminar on Energy Efficiency [illegible] Sustainable World, Figures 24 and 32.

[37]Goldemberg *et al*, *op cit*, Ref 27, pp 479–481.

[38]See *Ibid*; H. Geller, 'Implementing electricity conservation programs: progress towards least-cost energy services among US utilities', in Johansson *et al*, *op cit*, Ref 7, pp 741–764; R.H. Williams, 'Innovative approaches to marketing electric efficiency', in Johansson *et al*, *op cit*, Ref 7, pp 741–764.

[39]D. Moskovitz, *Profits & Progress Through Least-Cost Planning*, National Association of Regulatory Utility Commissioners (NARUC), Washington, DC, USA, 1989; and O. de la Moriniere, 'Energy service companies: the French experience', in Johansson *et al*, *op cit*, Ref 7, pp 811–830.

[40]Geller, *op cit*, Ref 7.

[41]As the incentive to participate, manufacturers submitting proposals were paid approximately \$16 000. As an incentive to exceed the target efficiency level, approximately \$80/refrigerator will be paid to the manufacturer for each reduction of 15% in electricity-use beyond the target value given. The procurement guidelines also invited manufacturers to create an 'energy label' to compare the energy-use of their design to that of models already on the market. Personal communication, Hans Nilsson, National Energy Administration, Sweden, 10 August 1990.

[42]This is the annual tax proposed to support three climate change initiatives: (1) a CFC phase-out; (2) reforestation of 12 million hectares/year; and, (3) fossil-fuel energy conservation in the developing world. See J. Goldemberg, 'Policy responses to global warming', in J. Legget, ed, *Global Warming*, Oxford University Press and Greenpeace International, London, p 177.

[43]For a more detailed discussion of carbon taxes, see M. Grubb, *The Greenhouse Effect: Negotiating Targets*, The Royal Institute of International Affairs, London, UK, 1989.

[44]F. von Hippel and B.G. Levi, 'Automotive fuel efficiency: the opportunity and weaknesses of existing market incentives', *Resources and Conservation*, No 10, 1983, pp 103–124.

[45]For a description of the methodology used to determine appliance standard levels in the USA, see USDOE, *Technical Support Document: Energy Conservation Standards for Consumer Products-Refrigerators and Furnaces*, Report Number DOE/CE-0277, Washington, DC, USA, 1989. For proposed lighting and motor standards, see, for example, *An Act Requiring Minimum Energy Efficiency Standards for Lighting Fixtures, Lightbulbs, Floor Lamps, Table Lamps and Electric Motors*, House Bill number 5239, (1990), The Commwealth of Massachusetts; and *An Act Reducing The Greenhouse Effect by Promoting Clean and Efficient Energy Sources*, House Bill number 5277 (1990), The Commonwealth of Massachusetts, USA.

[46]B. Keepin and G. Kats, 'Greenhouse warming: comparative analysis of nuclear and efficiency abatement strategies', *Energy Policy*, Vol 16, No 6, December 1989, pp 537–642.

[47]R.H. Williams and H.A. Feiveson, *Diversion-Resistance Criteria for the Future Nuclear Power*, Princeton Center for Energy and Environmental Studies, Princeton, NJ, USA, 1989.

[48]International Energy Agency, *Energy Policies and Programmes of IEA Countries*, IEA, Paris, 1989.

[49]For examples of cost-effective government R&D in the buildings sector, see H. Geller, J.P. Harris, M.D. Levine and A.H. Rosenfeld, 'The role of Federal research and development in advancing energy efficiency: a \$50 billion contribution to the U.S. economy', *Annual Review Energy*, No 12, pp 537–395; M.A. Brown, L.G Berry and R.K. Goel, 'Commercializing Government-sponsored innovations: twelve successful buildings case studies', Oak Ridge National Laboratory, Report No ORNL/CON-275, Oak Ridge, TN, USA, 1989.

[50]See Goldemberg, *et al*, *op cit*, Ref 33. In the low-carbon scenario, electricity demand grows by 4%/year, and would be met with the following generation mix: BIG/GT (32%), hydropower (31%), natural gas (17%%), PV/wind/solar thermal (10%), coal (6%), and nuclear (2%).

[51]United States Environmental Protection Agency, *op cit*, Ref 35.

[52]Steps 1 and 3–11 are adapted from H. Geller, *National Energy Efficiency Platform: Description and Potential Impacts*, American Council for an Energy-Efficient Economy, Washington, DC, USA, 1989. Step 2 involves measures to reduce ambient temperatures, ie, the 'heat-island effect' in cities, personal communication, Arthur Rosenfeld, Lawrence Berkeley Laboratory, 1989.

[53]The least-emissions case is the 'high-efficiency/environmental-dispatch scenario' and the no-policy case is the 'reference scenario/economic dispatch scenario' as described in Bodlund *et al*, *op cit*, Ref 30.

[54]International Energy Agency, *op cit*, Ref 48.

Appendix 1

Methodology for calculating the cost of avoiding greenhouse gas emissions

Quantifying and comparing greenhouse gases other than CO_2

In comparing the emissions from various fuels and technologies, we include the known effects of CO_2, CH_4 and tropospheric ozone (O_3) from methane oxidation and, in the case of automobiles, (N_2O).[55] We incorporate fuel-cycle emissions associated with mining, processing, transporting and burning the fuels. The greenhouse properties of each gas are expressed in terms of carbon-equivalents and added together. We use natural gas leakage rates of 1% of production for new distribution systems. Emissions from own-use (on-site) energy and those related to the energy embodied in materials are not included. Doing so would, in many cases, improve the attractiveness of efficiency and renewables in comparison to traditional energy systems.

Since the atmospheric residence times of greenhouse gases differ, it is necessary to choose a time period under which comparisons of the gases' relative greenhouse forcing will be made. In this article, we use a 20-year period in order to incorporate the effect of the gases on the rate of climate change and to give a fair basis for evaluation of measures and policies aimed at buying time in a near-term perspective (ie, 0 to 20 years). A long-term (100 years or more) perspective would discount the role of methane emissions in our comparisons.

The resulting carbon-equivalent emissions factors are (grams/MJ): Coal 30.6; oil 24.6; natural gas 17.2; and gasoline 25.7.[56] When shifting from a 20-year to a lifetime perspective (ie, integrating from zero to infinity), carbon-equivalent emissions decline by 19.6% for coal, 16.7% for oil, and 19% for natural gas.

$$\frac{\textit{Cost of a given measure} - \textit{Cost of base-case measure}}{\textit{Emissions from base-case measure} - \textit{Emissions from the given measure}} = \frac{\textit{Net cost (\$)}}{\textit{Net emissions (tonnes)}}$$

Figure 1.

Estimating the net cost (benefit) of avoiding greenhouse gas emissions

To compare various technical and fuel-choice measures for reducing emissions, to the corresponding base case, we use an indicator called the cost of avoided carbon-equivalent (CAC_{eq})[57] which is shown in Figure 1.

The following is an illustration based on conserving coal-based electricity with adjustible-speed motor drives (7th item in Appendix 2, Table 1). The levelized cost of conserved electricity is \$0.0111/kWh) *v* an electricity supply cost of \$0.0436/kWh (busbar cost). The electricity production results in emissions of 318 grams of carbon-equivalent/kWh$_e$. Choosing the efficiency strategy would result in a cost of avoided carbon-equivalent with a net economic benefit:

$$\frac{0.0111\ \$/\text{kWh} - 0.0436\ \$/\text{kWh}}{318\ \text{grams Ceq/kWh} - 0\ \text{grams Ceq/kWh}} = -\$102/\text{tonne carbon-equivalent}$$

Emissions associated with the measure are zero for efficiency strategies, but are positive for substitution to fuels with net emissions of greenhouse gases.

[55]Deborah Wilson, 'Quantifying and comparing fuel-cycle greenhouse gas emissions from coal, oil and natural gas consumption', *Energy Policy*, Vol 18, No 6, July/August 1990, pp 550–562.

[56]Motor fuel emissions rates are derived from DeLuchi *et al*, *op cit*, Ref 9, based on Wilson, *Ibid*.

[57]For further detail on this method (as applied to carbon emissions), see F. Krause and J. Koomey, 'Unit costs of carbon savings from urban trees, rural trees, and electricity conservation: a utility cost perspective', *Proceedings of the Workshop on Saving Energy and Reducing Atmospheric Pollution by Controlling Summer Heat Islands*, Lawrence Berkeley Laboratory, Report No 27872, CA, USA, 1989.

Appendix 2

Examples of the cost of avoiding greenhouse gas emissions

In order to evaluate and rank the economic efficiency of technologies to reduce greenhouse gas emissions we have constructed a list of examples of specific measures and their costs (Tables 1, 2, and 3). These measures are grouped into three categories: electricity, heating and transportation and include efficient end-use technologies, conversion technologies and fuel substitution options. In each category, a base case is chosen (eg, power production with coal or natural gas) and its costs and emissions are compared with those of alternatives (eg, efficient lighting equipment). The Tables distinguish between available and emerging technologies. Data are not yet available to enable the consistent and comprehensive inclusion of indirect infrastructure-related costs.

The results incorporate CO_2 and other important greenhouse gases. The economic results are expressed in terms of the cost of avoided carbon-equivalent: CAC_{eq} (ie, the cost of a strategy to reduce emissions minus the cost of a base-case strategy, divided by the amount of emissions reduced (\$/tonne)). A negative CAC_{eq} corresponds to a net economic benefit, ie the cost of the emissions-reducing strategy is lower than the cost of the base-case strategy. Appendix 1 shows a sample calculation and describes our method of treating emissions in more detail.

The costs of avoided fuels are listed under the headings for each Table. When comparing the results, care must be taken to focus both on the *cost* of avoided emissions and the *amount* of emissions avoided. A small quantity of avoided emissions and a relatively large cost differential will lead to a large CAC_{eq}, as in the case of coal gasification for electric power production. The percentage-reduction values shown in the Tables put each measure in perspective.

Table 1. Examples of avoided emissions and their costs: electricity.

Electricity[a]	**Measure Resource cost**	**Avoided emissions**		**Cost of avoided carbon-equivalent (CACeq)**
(Cost of avoided resource (coal): $0.44/kWhe)	**($/kWh)**	**(g Carbon-eq/kWh)**	(%)	**($/tonne)**
End-use efficiency[b]				
Available technologies				
Lighting (incandescent → compact fluorescent)	−0.011	318	100	−171
Lighting (efficient fluorescent tube)	−0.007	318	100	−159
Lighting (lamps, ballasts, reflectors)	0.013	318	100	−96
Refrigerator/freezer, no CFCs	0.018	318	100	−79
Freezer, automatic defrost, no CFCs	0.022	318	100	−67
Heat pump water heaters	0.034	318	100	−30
Variable-speed motor drive	0.011	318	100	−102
US field data, multifamily, leaking retrofits	0.038	318	100	−19
Retrofits in 450 US commercial buildings	0.026	318	100	−54
No-cost or behavioural measures	0	318	100	−137
Electricity production[c] (busbar costs)				
Available technologies				
Biomass steam-electric (woodfuel)	0.041	318	100	−9
STIG (gasified coal)	0.041	9	3	−313
STIG (natural gas)	0.027	163	51	−103
Wind (1988)	0.054	318	100	33
Solar thermal electric (1988)	0.114	318	100	221
Solar photovoltaics (1988)	0.231	318	100	588
Nuclear	0.057	318	100	41
Emerging technologies				
ISTIG (gasified coal)	0.034	57	18	−176
ISTIG (natural gas)	0.024	187	59	−106
Chemically recuperated gas turbine	0.029	204	64	−73
Solar thermal electric				
(2000)	0.043	318	100	−1
(2010)	0.036	318	100	−24
(2020)	0.031	318	100	−40
Solar photovoltaics				
(2000)	0.072	318	100	89
(2010)	0.050	318	100	22
(2020)	0.036	318	100	−24
Wind				
(2000)	0.033	318	100	−33
(2010)	0.027	318	100	−51
Nuclear – industry target for USA	0.040	318	100	−11
Fuel choice (STIG technology in all cases)				
Avoided resource costs (gasified coal): $0.071/kWh)				
Gasified coal → natural gas (1990)	0.027	155	50	−91
Gasified coal → biomass (sugar) (~2000)	0.033	309	100	−25

Notes: [a] Unless noted, the annualized costs of efficiency and supply measures are calculated with a 6% real discount rate and no taxes. Costs for electric power plants are amortized over a 30-year period. Efficiencies based on higher heating value (HHV) are used throughout this analysis. The reference (avoided) technology is a coal (2 × 500 MW) steam-electric plant, 34.6% efficiency, $1370/kW capital cost, and operations and maintenance (O&M) costs of ¢0.89/kWh. For all power plant costs: 70% capacity factor, coal price $1.79/GJ, natural gas price $2.10/GJ. [b] Three lighting examples: The first two measures result in a net benefit because reduced labour costs exceed incremental capital costs[58] (7% real discount rate); Refrigerator and freezer without CFCs: assumes a blend of hydrochlorofluorocarbons (HCFC-22, HFC-152a, and HCFC-124) with 97% lower ozone-depleting potential than the CFC-12 refrigerant currently used. For foam insulation, today based on CFC-11 as a blowing agent, alternatives are based on HCFC-141b and HCFC-123 which in fact have higher insulating values than current foams (7% real discount rate);[59] Variable-speed motor drive: ABB Corporate Research (personal communication, Lars Gertmar, 1988). Capital cost $104/kW (750 kW motor). Assumes installation costs equal to 8% of capital cost; 15-year lifetime; 4 000 hours/year; 35% reduction in electricity requirement; Heat-pump water heater: adapted from Brown *et al*, assuming 2 000 kWh/year reduction in electricity required, 10-year life;[60] US field data, multi-family space heating: includes measured data from 42 actual projects in the USA.[61] [c] STIG (Steam-injected gas turbine) for gasified coal: 2 × 50 MW steam-injected gas turbine (STIG), air-blown gasifier, hot-gas clean-up, 35.6% efficiency, $1 300/kW capital cost and ¢0.71/kWh O&M costs; STIG for natural gas: 4 × 51 MW, 40% efficiency, $410/kW capital cost and ¢0.29/kWh O&M costs; Chemically recuperated gas turbines: assumes 54% efficiency, $500/kW capital cost, 70% capacity factor.[62] O&M costs assumed same as for gas-fired STIG systems; Biomass-steam $1 500/kW capital cost, $0.005/kWh O&M, $1.5/GJ fuel cost, wind, solar, thermal, and solar photovoltaics.[63] These prices are based on the RD&D intensification scenarios developed by five US National Laboratories; Nuclear: see, *op cit*, Ref 7; ISTIG (intercooled STIG) coal: 110 MW, 42.1% efficiency, $1 030/kW capital cost and ¢0.60/kWh O&M costs; gas: 114 MW, 47% efficiency, $400/kW capital cost and ¢0.29/kWh O&M costs; Fuel choice: the coal base-case is gasified coal *v* natural gas:[64] Gasified coal *v* biomass: 111 MW BIG/ISTIG system.[65]

Table 2. Examples of avoided emissions and their costs: heating and fuel choice.

Heating and fuel choice	**Measure resource cost**	**Avoided emissions**		**Cost of avoided carbon-equivalent (CACeq)**
(Cost of avoided resource (oil): $5.56/GJ)	**($/GJ)**	**(g Carbon-eq/MJ)**	(%)	**($/tonne)**
End-use efficiency[a]				
Available technologies				
Low-emissivity window glass	1.75	25	100	−155
Flame retention head burners	0.93	25	100	−188
US field data, multi-family, heating retrofits	3.00	25	100	−104
No-cost or behavioural measures	0	25	100	−226
Fuel choice[b]				
Methanol (from sugar industry)(~2000)	11.53	31	100	−95
Biomass (1990)				
High price (Sweden)	3.00	25	100	−104
Low price (Brazil)	1.50	25	100	−165
Biomass in district heating (including capital costs + O&M)				
1990	9.94	35	100	63
2010	8.46	35	100	−4

Notes: [a] Low-emissivity window glass: transmittance reduction of 0.23 W/m^2-K in a climate with 3 316 HDD(C);[66] Flame retention head burners: assumes 18% fuel-requirement reduction, $300 incremental cost, 10-year life;[67] US field data, multi-family space heating: includes measured results for 111 actual retrofit projects around the USA.[68] [b] For comparison, the reference feedstock is coal; Methanol: near-term technology assumed to be the pressurized, steam/oxygen-blown, fluidized bed biomass gasifier that has been developed by the Institute of Gas Technology, in plant sizes of 101.5 million gallons/year production capacity. Costs are significantly lower ($8.56/GJ) for a 555.6 million-gallon-per-year plant.[69] Biomass in district heating: calculations are for Swedish conditions, assuming 4 000 hours/year operation, 20-year economic life, $370/kW capital cost, 88% thermal efficiency, $5.22/GJ fuel price (coal) in 1990 and $3.92/GJ in 2010.

Table 3. Examples of avoided emissions and their costs: transport.

Passenger cars[a]	**Measure resource cost**	**Avoided emissions**			**Cost of avoided carbon-equivalent (CACeq)**
End-use efficiency[b]	**($/GJ)**	**(kg/GJ)**	(%)		**($/tonne)**
(Cost of avoided resource: $12.63/GJ (high); $5.17/GJ (low)					
Available technologies					
US CAFE standards (16.8 to 8.7 l/100km)	0.86	26	100	−458	−168
Average (8.7 to 6.2 l/100km)	5.17	26	100	−290	0
No-cost or behavioural measures	0	26	100	−492	−201
Fuel Choice[c]	($/100 km)	(kg/100km)	(%)		
(Cost of avoided resource: $1.2/100km (low), $2.9/100km (high))					
Gasoline → compressed natural gas	-		Higher emissions than from gasoline		
Gasoline → methanol from natural gas	-		Higher emissions than from gasoline		
Gasoline → methanol from coal	-		Higher emissions than from gasoline		
Gasoline → methanol from biomass (present)	3.10	7.5	100	22	253
Gasoline → methanol from biomass (near-term)	1.70	7.5	100	−164	67
Electric cars (operating-cost comparison)					
Gasoline → electric car (natural gas)	0.19	6.4	86	−427	−158
Gasoline → electric car (biomass)	0.29	7.5	100	−352	−122

Notes: [a] Reference-technology emissions for passenger cars: gasoline (7 500 gCeq/100 km, at current US new-car average fuel economy of 8.4 litres/100 km); [b]Gasoline prices: Gasoline prices (excluding taxes) vary amongst industrialized countries. We show cost calculations for the two extreme ends of the range. The 'high' gasoline price is from Japan and the 'low' price from the USA. Fleet improvement: This reflects measures already used in the automobile industry, applied nationally (USA) without changing the size distribution of the car stock.[70] The manufacturing costs of these measures should be comparable in the other major automobile-producing countries. The potential application of the measures to new cars sold outside of the USA depends on the extent to which they are already in use;[71] [c] Fuel choice: Because the energy content of methanol and the energy efficiency of methanol cars differ from those of gasoline and gasoline-fueled cars, we show costs in terms of $/100km. For methanol cars, we use a vehicle efficiency that is 15% higher than that of gasoline-fueled cars. The assumed gasoline fuel efficiency is 8.4 litres/100km, the US average for new cars. The biomass feedstock price for methanol production is $2.33/GJ (both cases). The coal price is $1.48/GJ. Through an extensive literature review, Sperling and DeLuchi concluded that the vehicle price and maintenance costs for single-fuel methanol cars will become comparable to those for similar gasoline cars (ie, with same size, range, weight, vehicle life and power) in the near-term.[72] The only cost differential associated with owning and operating a methanol car, therefore, will be that of the fuel. Although methanol fuels (from natural gas or biomass) cost more per unit of energy than gasoline today,[73] part of this price differential will be balanced by the inherently better efficiency of methanol cars. Fuel-switching from gasoline to methanol manufactured from natural gas would increase the carbon-equivalent emissions per vehicle kilometre driven. The difference, however, is small and must be weighed against the potential role of natural gas as a transition fuel while biomass-based methanol supplies are made available; Electric cars: The calculations for electric cars are based on GM's prototype Impact discussed in the text, assuming the electricity is made with the currently available power plants (the first and third entries under the 'Electricity Production' heading in Table 1). The comparison is based strictly on operating costs.

[58]M.A. Piette, F. Krause and R. Verderber, *Technology Assessment: Energy-Efficient Commercial Lighting*, Lawrence Berkeley Laboratory, Report No 27032, CA, USA, 1989.
[59]See United States Environmental Protection Agency, *op cit*, Ref 51.
[60]Brown *et al*, *op cit*, Ref 49.
[61]C.A. Goldman, K.M. Greely and J.P. Harris, *Retrofit Experience in the U.S. Multifamily Buildings: Energy Saving, Costs, and Economics*, Lawrence Berkeley Laboratory, Report No 25248 1/2, CA, USA, 1988, p 24.
[62]California Energy Commission, *op cit*, Ref 19.
[63]Solar Energy Research Institute, *op cit*, Ref 6. The costs shown in this report include taxes (ie a fixed charge rate is used). We recalculated the costs using a 6% real discount rate and no taxes.
[64]Williams and Larson, *op cit*, Ref 7.
[65]Ogden *et al*, *op cit*, Ref 21.
[66]Geller *et al*, *op cit*, Ref 49.
[67]Brown *et al*, *op cit*, Ref 49.
[68]Goldman *et al*, *op cit*, Ref 61.
[69]R.H. Williams, *Will Constraining Fossil Fuel Carbon Dioxide Emissions Really Cost So Much?*, Center for Energy and Environmental Studies, Priceton University, NJ, USA, 1990.
[70]Personal communication, David L. Greene, Oak Ridge National Laboratory, 14 May 1990.
[71]D. Sperling and M.A. DeLuchi, 'Is methanol the transportation fuel of the future?', *Energy*, Vol 14, No 8, pp 469–482.
[73]Williams, *op cit*, Ref 69.